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RESEARCH MEMORANDUM

EFFECT OF SURFACE-ACTIVE ADDITIVES ON PHYSICAL PROPERTIES OF SLURRIES OF VAPOR-PROCESS MAGNESIUM

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
November 3, 1955

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF SURFACE-ACTIVE ADDITIVES ON PHYSICAL PROPERTIES OF SLURRIES OF VAPOR-PROCESS MAGNESIUM

By Murray L. Pinns

SUMMARY

Slurry fuels consisting of approximately 50 percent vapor-process magnesium, JP-1 fuel, and surface-active additive were studied. Brookfield apparent viscosities, plastic viscosities, and yield values of the slurries decreased progressively with increasing concentration of additive up to a concentration of 3 to 5 percent, based on the weight of slurry. Greater concentrations of additive had little effect on viscosity and yield value or caused a small increase. As the concentration of additive was increased from 0 to about 2 percent, the slurry appeared to change from a thixotropic to a nonthixotropic material. All the slurries prepared settled relatively little, compared with slurries of 1.5-micron atomized magnesium, and the settled portion was soft and easily remixed. The most fluid slurries of vapor-process magnesium were much thicker than the most fluid slurries with a similar concentration of 1.5-micron atomized magnesium. The lowest Brookfield apparent viscosity obtained for a slurry made with 49 percent vapor-process magnesium was 3050 centipoises at room temperature, while the lowest plastic viscosity was 28 centipoises and the lowest yield value was 140 dynes per square centimeter.

Of the 13 additives tested at a concentration of 2.0 percent, the 7 that were the most effective in reducing the Brookfield apparent viscosity contained a hydroxyl group plus an ester or polyoxyethylene group in the molecule. The most effective of the 7 was polyoxyethylene dodecyl alcohol (8 moles ethylene oxide per mole dodecyl alcohol). The effect of the additives in reducing the yield value was relatively the same as the effect of reducing the Brookfield apparent viscosity, but was not relatively the same as the effect of reducing the plastic viscosity.

The densities of slurries containing 2.0 to 6.0 percent polyoxyethylene sorbitol tetraoleate ranged from 1.098 to 1.114 grams per cubic centimeter at 30° C (86° F).

[redacted]

INTRODUCTION

Investigations at the NACA Lewis laboratory have indicated that magnesium slurry fuels offer advantages over conventional hydrocarbon aircraft fuels in the greater thrust and wider operating limits obtainable (ref. 1). Magnesium slurry has been used successfully as fuel in missiles flown at the NACA Wallops Island test station (ref. 2). The use of more finely divided magnesium results in a higher blow-out velocity (ref. 1). However, with about 50 percent of very finely divided magnesium (average equivalent spherical diameter less than 2 microns), it is necessary to incorporate surface-active additives to make the slurry sufficiently fluid to permit satisfactory pumping and atomization. These additives affect rheological characteristics, settling behavior, and density, which in turn govern the effective use of the slurries as fuels.

3834

The most finely divided magnesium now available for slurry preparation is made by the vapor-condensation process at the Lewis laboratory (ref. 3). The effect of temperature on the rheology of slurries of vapor-process magnesium is reported in reference 4. A study of the effect of surface-active additives on slurries containing 1.5-micron atomized magnesium is discussed in a previous report (ref. 5). The purpose of the present report is to extend that study to slurries made with the vaporized product.

Thirteen additives shown in reference 5 to represent a range of effectiveness in modifying the properties of the slurries were chosen for evaluation in slurries containing 49 or 51 percent vapor-process magnesium. This report presents flow curves, apparent viscosities, plastic viscosities, and yield values of slurries containing 0.5 to 6.0 percent additive. The settling characteristics and densities of some of the slurries are also reported.

MATERIALS AND PROCEDURE

Materials

<u>Magnesium</u>. - The magnesium was prepared at the Lewis laboratory by the vapor-condensation process described in reference 3. The starting material for this investigation was a concentrated paste of magnesium in hydrocarbon, prepared by centrifuging the dilute hydrocarbon suspension of magnesium obtained from the vaporizing process. The hydrocarbon used in the preparation of the dilute suspension was JP-1 fuel (MIL-F-5616) that had been passed through activated alumina. Two batches of magnesium paste were used; they will be designated as FP-1 and FP-2. Only six slurries were prepared with FP-2, and unless otherwise indicated, the slurries to be discussed were made with FP-1.

The FP-1 paste consisted of 58 percent solids and 42 percent JP-1 fuel. The solids consisted of 87 percent elemental magnesium, the other 13 percent presumably being magnesium oxide. Electron micrographs (such as fig. 1) indicate that the particles were generally either cubic or hexagonal. It has been estimated by the Dow Chemical Co. from electron micrographs they prepared that the particle size ranged largely from 0.06 to 0.2 micron, with occasional particles as large as 0.4 micron. Since an electron micrograph shows only a very small field, a photomicrograph was also taken (fig. 2), which indicates that essentially all the particles were smaller than 2 microns.

The FP-2 paste was similar to FP-1, except that the hydrocarbon was JP-5 fuel, and approximately 0.5 percent glycerol sorbitan laurate was present. The paste contained 68 percent solids, of which 92 percent was elemental magnesium.

<u>Hydrocarbon</u>. - The magnesium pastes were diluted as required with the hydrocarbon effluent obtained from the centrifuging process by which the magnesium paste FP-1 was obtained. The physical properties of this hydrocarbon are listed in table I.

<u>Additives</u>. - The 13 commercially available surface-active additives that were used were chosen to represent a wide range of surface activity in magnesium slurries on the basis of the findings reported in reference 5. These additives and their chemical composition are listed in table II, where they are designated by the same code numbers as in reference 5. The physical properties of the additives, as reported by the manufacturers, are also given in reference 5.

Preparation of Slurries

The appropriate quantities of additive and hydrocarbon were weighed into clean, new, one-pint paint cans, and warmed, if necessary, to disperse the additive. The required quantity of magnesium paste was added, and the air space in the can was purged with argon. The sealed can was shaken for 30 minutes on a paint conditioner and was then set in a 30° C (86° F) water bath. Slurries made with FP-1 paste weighed 400 grams and contained 49 percent solids (percentage not including the additive). Those with FP-2 paste weighed 450 grams and contained 51 percent solids.

Testing Procedure

The slurries were aged as described in appendix A before tests were run. Prior to each test, the can of slurry was shaken for 10 minutes on the paint conditioner. Each time the can was opened, the air space was purged with argon before the can was sealed again.

Flow curves, plastic viscosity, and yield value. - Flow curves (rheological terms are defined in appendix B) of the slurries were obtained at approximately 30° C (86° F) at rates of shear up to about 1000 reciprocal seconds by means of a modified Stormer viscometer. The instrument and its operation are described in references 5 and 6. Only the number 2 cup and bob were used. When the down curve of the flow curve had a linear portion, the plastic viscosity of the slurry was calculated from the slope, and the yield value was obtained by determining where the extrapolated linear portion intersected the load axis. The following equations were used, and are based on the Reiner and Riwlin equation (quoted in ref. 7) and instrumental constants: 3834

$$U = \frac{4.0}{\text{Slope of linear portion}}$$

$$f = 2.3\ (W_0 - 7)$$

where

U plastic viscosity, centipoises

f yield value, dynes/sq cm

W_0 intercept of extrapolated linear portion with load axis, g

Determinations of the plastic viscosity on two or more portions of the same material always agreed within 10 percent of the mean, usually within 5 percent of the mean. Determinations of the yield value agreed within 10 percent of the mean.

The flow curve of one slurry was obtained with the automatic concentric-cylinder rotational viscometer described in reference 8 because the slurry was too thick to be tested with the Stormer viscometer.

Brookfield apparent viscosity. - The Brookfield apparent viscosity, which is a one-point measurement of apparent viscosity at a low rate of shear, was determined at 30° ±1° C (86° ±2° F) with a model LVF Brookfield Synchro-lectric viscometer. The number 3 spindle at 12 rpm (estimated rate of shear, 10 sec^{-1}) was used for viscosities below 10,000 centipoises, and the number 4 spindle (estimated rate of shear, 0.5 sec^{-1}) was used for higher viscosities. The measurements were made in the same pint cans in which the slurries were prepared. First the slurry was shaken on the paint conditioner for 10 minutes. The viscometer spindle was then immersed to the mark for 30 ±1 seconds before the reading was taken. For reasons explained in appendix A, the Brookfield apparent viscosities reported are the average of readings obtained at approximately 2-week intervals during a period of 6 weeks or longer following an aging period of 30 days.

Sedimentation volume. - The extent of settling of some of the slurries in ordinary 50-milliliter graduated cylinders is reported as the sedimentation volume. Approximately 50 cubic centimeters of the well-mixed slurry was poured into the clean, dry cylinder, which was then tightly sealed and set in a water bath kept at $30^{\circ} \pm 0.5^{\circ}$ C ($86^{\circ} \pm 1^{\circ}$ F). When the magnesium settled, it formed a rather sharply demarcated layer. The volume of the settled portion was measured at the end of 28 days, and the sedimentation volume was calculated from the equation

3834

$$\text{Sedimentation volume} = \frac{\text{cc of sediment}}{\text{g of magnesium}} = \frac{v}{v_0 \rho c}$$

where

v volume of sediment, cc

v_0 volume of slurry, cc

ρ density of slurry, g/cc

c concentration of magnesium, fraction by weight

In addition, estimates were made of the volumes of supernatant liquids appearing in the pint cans of slurry at 2-week intervals during which the slurry had been at room temperature and had not been disturbed.

Density. - The densities of some of the slurries were determined at $30^{\circ} \pm 0.5^{\circ}$ C ($86^{\circ} \pm 1^{\circ}$ F) with a wide-mouth (Hubbard-Carmick type) pycnometer. Repeat determinations agreed within 0.003 gram per cubic centimeter of the mean.

RESULTS AND DISCUSSION

Flow curves were obtained for vapor-process-magnesium slurries containing a range of concentrations of various surface-active additives. The shape of the flow curve, the plastic viscosity and yield value calculated from the flow curve, and the Brookfield apparent viscosity were correlated with the concentration and type of additive. In addition, the extents of settling and densities of some of the slurries were measured. Comparisons were made between the results of this investigation and the results of a previous study (ref. 5) on the effects of surface-active additives on slurries containing 50 percent 1.5-micron atomized magnesium.

The rheological terms used in this discussion are defined in appendix B. There are some comments about the flow curves and viscosity measurements in appendix A.

Effect of Concentration of Additive

Flow curves. - The flow curves of slurries containing 49 percent magnesium and 0, 0.5, 1.0, and 2.0 percent polyoxyethylene sorbitol tetraoleate (A132) that are shown in figure 3 are typical of the flow curves obtained with the various additives. Figure 3(a) was obtained with the automatic concentric-cylinder rotational viscometer (ref. 8), the others with the Stormer viscometer. With no additive present, the slurry appeared to be pseudoplastic and thixotropic (fig. 3(a)). However, the latter characteristic did not show up consistently. 3834

With the addition of 0.5 percent A132, thixotropy was definitely present (fig. 3(b)), and the down curve had a relatively long linear portion, indicating that the behavior of the slurry was similar to that of a plastic material. When 1.0 percent A132 was present, there was less displacement of the down curve from the up curve than with 0.5 percent A132, indicating a lesser degree of thixotropy, and the down curve again had a relatively long linear portion (fig. 3(c)). With 2.0 percent (fig. 3(d)) or more A132, the up and down curves coincided (within experimental error), showing that the thixotropy had substantially been eliminated. The major portion of the curve was still linear, indicating plastic behavior.

The transition from a thixotropic slurry to one which was non-thixotropic as the concentration of additive was increased parallels the results reported for slurries of atomized magnesium in reference 5.

In some instances, the flow curves of the more fluid slurries of vapor-process magnesium had the down curve displaced slightly toward lower rates of rotation. This small displacement has no significance.

Plastic viscosity and yield value. - Plastic viscosities and yield values were determined from the flow curves of slurries containing a range of concentrations of each of the five additives A105, A118, A124, A130, and A132. All the results obtained are listed in table III, and those for A132 and A105, which are typical, are plotted in figure 4.

The plastic viscosity appeared to decrease to a shallow minimum with 3 to 5 percent additive. Actually, the variation in viscosity when more than 3 percent additive was used was within experimental error. The yield value decreased with increasing concentration of additive and either went through a minimum as in figure 4(a), or leveled off as in figure 4(b). The use of 3 to 4 percent additive gave the lowest yield values that were attained. The lowest plastic viscosities obtained with these slurries were about 3 to 5 times higher than the lowest obtained with the same additives in slurries of atomized magnesium, while the corresponding yield values were about 20 to 30 times greater.

Brookfield apparent viscosity. - The change in Brookfield apparent viscosity with concentration of additive generally followed the same trend as did the yield value. This can be seen in table III and figures 4(a) and (b) for additives A105, A118, A124, A130, and A132. From 3 to 5 percent additive was required to obtain the lowest Brookfield apparent viscosities. The lowest Brookfield viscosities were generally 20 to 30 times as great as the lowest obtained with the same additives in slurries of atomized magnesium (ref. 5).

3834

Comparison of Additives

The relative effectiveness of the additives was compared on the basis of the properties of slurries containing 2 percent of additive. This concentration was chosen in order to minimize the effect of the additive in decreasing the heating value of the slurry fuel. At the same time, this concentration gave viscosities and yield values not much higher than the lowest obtainable, which would have required 3 to 5 percent of additive. The available data (table III) indicate, however, that the relative effectiveness of the additives would be about the same at 3 to 5 percent as at 2 percent.

The additives evaluated in slurries of FP-1 magnesium paste are listed in table IV in increasing order of Brookfield apparent viscosity of the slurry. This table shows that the yield values changed in substantially the same order as the Brookfield viscosities, while the plastic viscosities were not in the same order.

The relative effectiveness of the additives in reducing the Brookfield apparent viscosities of slurries of FP-1 magnesium was very much like that reported for the same additives in slurries of atomized magnesium (ref. 5). As in reference 5, the most effective additives were those which contain a hydroxyl group plus an ester or polyoxyethylene group in the molecule. Additives A109, A118, A130, A131, and A132, which were the most effective of those tested in the present investigation, are all of this type. Of these five additives, A130 was the best, not only in reducing the Brookfield apparent viscosity, but also in giving a markedly lower plastic viscosity and yield value than any of the other additives.

In order to confirm the greater effectiveness of A130 (polyoxyethylene dodecyl alcohol made with 8 moles ethylene oxide per mole dodecyl alcohol) several 51-percent-magnesium slurries were made with magnesium FP-2 and 2 percent of additive. The additives used were A130, A129, A128, and A109. The A109 was used as a basis of comparison, since it was also used in slurries made with FP-1 magnesium and gave a Brookfield viscosity very similar to that obtained with A128 or A132.

The compositions of A128 and A129 are similar to that of A130, but they are made with only 2 and 4 moles of ethylene oxide, respectively. As shown in table IV, A130 again gave a lower Brookfield apparent viscosity than A109. The Brookfield viscosity obtained with A129 was intermediate while that obtained with A128 was higher than the viscosity obtained with A109. It therefore appears that the effectiveness of this type of additive increases with the number of oxyethylene groups per molecule. However, there is probably an optimum number which gives maximum effectiveness. 3834

Other Characteristics

Settling. - Observation of the slurries of vapor-process magnesium in pint cans and in 50-milliliter graduated cylinders showed that these slurries settled much less than did the slurries of atomized magnesium (ref. 5). When slurries containing 1.0 to 5.0 percent lecithin (A118), which was one of the most effective additives, were permitted to settle in 50-milliliter graduated cylinders at 30° C (86° F), the quantity of supernatant liquid that accumulated in 28 days was almost negligible and was small even after four months. At 28 days, the sedimentation volume of these slurries ranged from 1.72 to 1.84 cubic centimeters per gram, where 1.86 cubic centimeters per gram would have indicated no settling.

When the pint cans of slurry were permitted to rest undisturbed for 2 weeks at room temperature, no more than about 20 cubic centimeters of supernatant liquid was ever observed to form in about 360 cubic centimeters of even the most fluid of the vapor-process-magnesium slurries, and the settled portion was always very soft and easily remixed. The slight settling and soft sediment, which are highly desirable characteristics, are in contrast to the extensive settling and hard cake of sediment often observed in the most fluid slurries of atomized magnesium (ref. 5).

Density. - The densities of slurries containing 2.0 to 6.0 percent A132 varied regularly with the concentration of additive and ranged from 1.098 to 1.114 (table V). The densities of slurries containing less of this additive could not be measured properly because air pockets were entrapped in the thick slurry in the pycnometer. No other methods of measuring density were tried.

SUMMARY OF RESULTS

A study of some of the physical properties of slurry fuels consisting of 49 percent vapor-process magnesium, various proportions of surface-active additive, and JP-1 fuel gave the following results:

1. The Brookfield apparent viscosity, plastic viscosity, and yield value of the slurries decreased progressively with increasing concentration of additive up to a concentration of 3 to 5 percent by weight of slurry. Greater concentrations had little additional effect or caused a small increase.

2. As the concentration of additive was increased, the slurry appeared to change from a thixotropic to a nonthixotropic material. Approximately 2 percent of polyoxyethylene sorbitol tetraoleate or lecithin was required to effect this change.

3. Of the 13 additives evaluated, those which gave the lowest Brookfield apparent viscosity and yield value contained a hydroxyl group plus an ester or polyoxyethylene group. Of 7 such additives, the most effective was polyoxyethylene dodecyl alcohol (8 moles ethylene oxide per mole of alcohol).

4. Even the most fluid slurries were much thicker (Brookfield apparent viscosity 20 to 30 times greater) than the most fluid slurries containing a similar concentration of 1.5-micron atomized magnesium. They settled much less and the settled portion was always very soft and easy to remix.

5. The densities of slurries containing 2.0 to 6.0 percent polyoxyethylene sorbitol tetraoleate ranged from 1.098 to 1.114 grams per cubic centimeter at 30° C (86° F).

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 30, 1955

3834
CR-2

APPENDIX A

COMMENTS ON VISCOSITY MEASUREMENTS

Brookfield Apparent Viscosity

The variation of Brookfield apparent viscosity with age of the slurry was often rather erratic, so that measurements made at 2-week intervals gave an irregular viscosity-time plot. In this respect, these vapor-process-magnesium slurries behaved more like the boron slurries described in reference 9 than like the slurries of atomized magnesium described in reference 5. The viscosities of slurries containing 2 percent or more additive frequently tended to decrease for about a month after preparation, while the viscosities of those containing less additive sometimes increased during this period. Because of the initial change and the erratic variation, the Brookfield viscosities reported are averages of readings obtained at approximately 2-week intervals during a period of 6 weeks or longer following an aging period of 30 days.

3834

Plastic Viscosity and Yield Value

There is also some evidence that the plastic viscosities and yield values of the slurries changed with age. When two slurries containing 4.0 and 6.0 percent A130 were aged, the plastic viscosities appeared to decrease to a minimum in about 30 days, while the yield values appeared to increase to a maximum in about 80 days. Since these variations were almost within experimental error, they may not be significant. All the plastic viscosities and yield values reported were obtained after the slurry had been aged for at least 60 days.

Effect of Prolonged Shear on Shape of Flow Curve

When the flow curve was such that the down curve was displaced from the up curve, the displacement sometimes disappeared when repeated up and down curves were obtained on the same portion of slurry without pausing. If this same portion of slurry was permitted to rest in the viscometer cup undisturbed for about an hour after the last down curve had been obtained, the displacement appeared again. Because of this behavior, each flow curve for which data are reported was obtained on a new portion of slurry.

3834

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APPENDIX B

GLOSSARY

Flow curve — A plot of rate of shear (ordinate) against shearing stress (abscissa). For a rotational viscometer, the rate of shear may be expressed as the rate of rotation of the cup or bob, and the shearing stress may be expressed as the load or torque applied. A plot obtained by measuring the rate of shear at successively increasing shearing stresses is called an up curve. For decreasing rates of shear, the plot is called a down curve.

Newtonian — A material for which the flow curve is a straight line passing through the origin.

Plastic — A non-Newtonian material for which the flow curve is a straight line (except possibly at very low rates of shear) which, when extrapolated, intersects the shearing-stress axis at a positive value.

Pseudoplastic — A non-Newtonian material for which the flow curve (both up curve and down curve) starts at the origin and is nonlinear and convex toward the shearing-stress axis.

Thixotropy — A condition in which the structure of a suspension is destroyed by agitation and is rebuilt upon rest. The condition is evidenced by a flow curve in which, for a given shearing stress, the rate of shear is higher on the down curve than on the up curve.

Viscosity, apparent — The reciprocal of the slope of a line drawn from the origin to any point on the flow curve.

Viscosity, plastic — The reciprocal of the slope of the linear flow curve exhibited by a plastic material.

Yield value — The value of the intercept of the extrapolated linear flow curve of a plastic material with the shearing-stress axis.

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3834

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3834

TABLE I. - PHYSICAL PROPERTIES OF HYDROCARBON

Distillation range, °F	
Initial boiling point	330
Percent evaporated	
5	343
10	355
20	363
30	373
40	380
50	390
60	401
70	413
80	432
90	460
95	488
Final boiling point	532
Residue, percent	1.0
Density at 86° F, g/cc	0.7944
Aromatics (silica gel), percent by volume	15.9

TABLE II. - ADDITIVES USED IN PREPARATION OF SLURRIES

Code number[a]	Chemical composition
A105	Cetyl alcohol
A109	Glycerol sorbitan laurate[b]
A113	Iron naphthenate
A116	Lead di(2-ethylhexoate)
A118	Lecithin (derived from soybeans)
A124	*n*-Octadecylamine
A127	Oleic acid
A128	Polyoxyethylene dodecyl alcohol (2 moles ethylene oxide)
A129	Polyoxyethylene dodecyl alcohol (4 moles ethylene oxide)
A130	Polyoxyethylene dodecyl alcohol (8 moles ethylene oxide)
A131	Polyoxyethylene dodecanethiol (3.5 moles ethylene oxide)
A132	Polyoxyethylene sorbitol tetraoleate
A136	Sodium dioctyl sulfosuccinate

[a]Ref. 5.

[b]Trade name G-672, used in preparation of slurry fuels discussed in refs. 4, 6, and 8.

TABLE III. - EFFECT OF CONCENTRATION OF ADDITIVE ON

VISCOSITIES AND YIELD VALUES OF SLURRIES[a]

3834

Additive	Additive concen-tration, percent	Brookfield apparent viscosity, centipoises	Plastic viscosity, centipoises	Yield value, dynes/cm^2
None	0	>100,000		
A105	2.0	9,480	40	450
	3.0	8,750	40	420
	4.0	8,820	37	420
	5.0	9,330	36	480
	6.0	9,450	40	510
A118	1.0	34,100	60	1010
	2.0	5,300	47	390
	3.0	3,300	43	220
	4.0	3,260	39	220
	5.0	3,500	41	220
A124	2.0	23,600	42	490
	3.0	9,360	40	440
	4.0	8,860	39	410
	5.0	8,590	40	440
A127	2.0	27,100		
	3.0	29,500		
	4.0	26,800		
A130	2.0	4,360	33	220
	4.0	3,140	29	150
	6.0	3,050	30	140
A132	.5	43,000	130	2400
	1.0	21,800	58	860
	2.0	8,130	40	400
	2.0	8,400	43	430
	3.0	5,960	33	320
	4.0	5,480	35	280
	5.0	5,490	33	280
	6.0	5,690	39	270

[a]Determined at 30° C (86° F).

3834

TABLE IV. - VISCOSITIES AND YIELD VALUES OF

SLURRIES CONTAINING 2.0 PERCENT ADDITIVE[a]

Additive	Brookfield apparent viscosity, centipoises	Plastic viscosity, centipoises	Yield value, dynes/cm^2
	Magnesium FP-1		
A130	4,360	33	220
A118	5,300	47	390
A132	8,130	40	400
A132	8,400	43	430
A109	8,380	46	480
A131	8,460	46	430
A105	9,480	40	450
A124	23,600	42	490
A127	27,100		
A116	33,800		
A136	36,500		
A113	39,600		
	Magnesium FP-2		
A130	2,680		
A130	2,820		
A129	3,280		
A109	3,750		
A109	3,760		
A128	3,840		

[a]Determined at 30° C (86° F).

TABLE V. - DENSITIES OF SLURRIES CONTAINING

VARIOUS CONCENTRATIONS OF A132

Concentration of A132 in slurry, percent	Density of slurry at 30° C (86° F), g/cc
2.0	1.098
3.0	1.101
4.0	1.106
5.0	1.110
6.0	1.114

3834

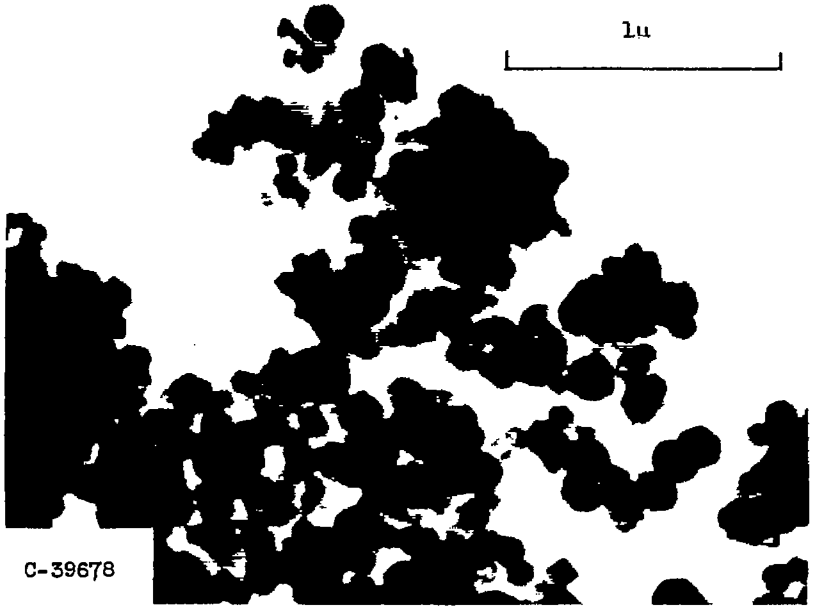


Figure 1. - Electron micrograph of vapor-process magnesium in FP-1.

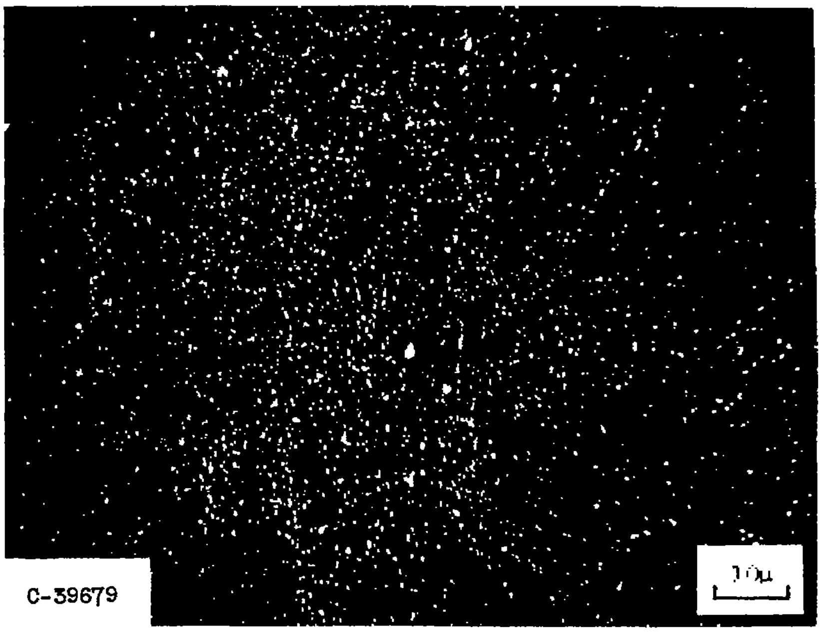
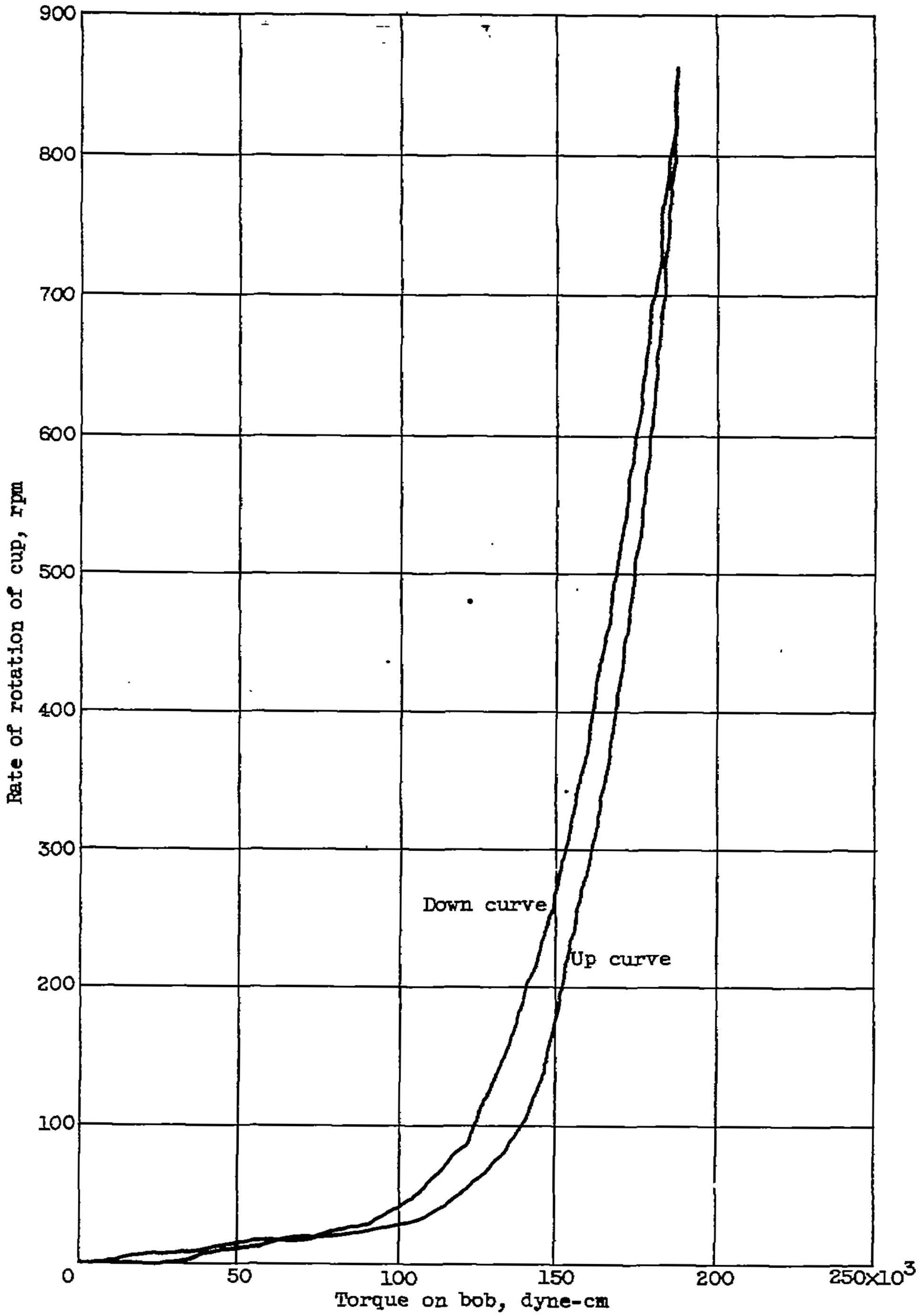


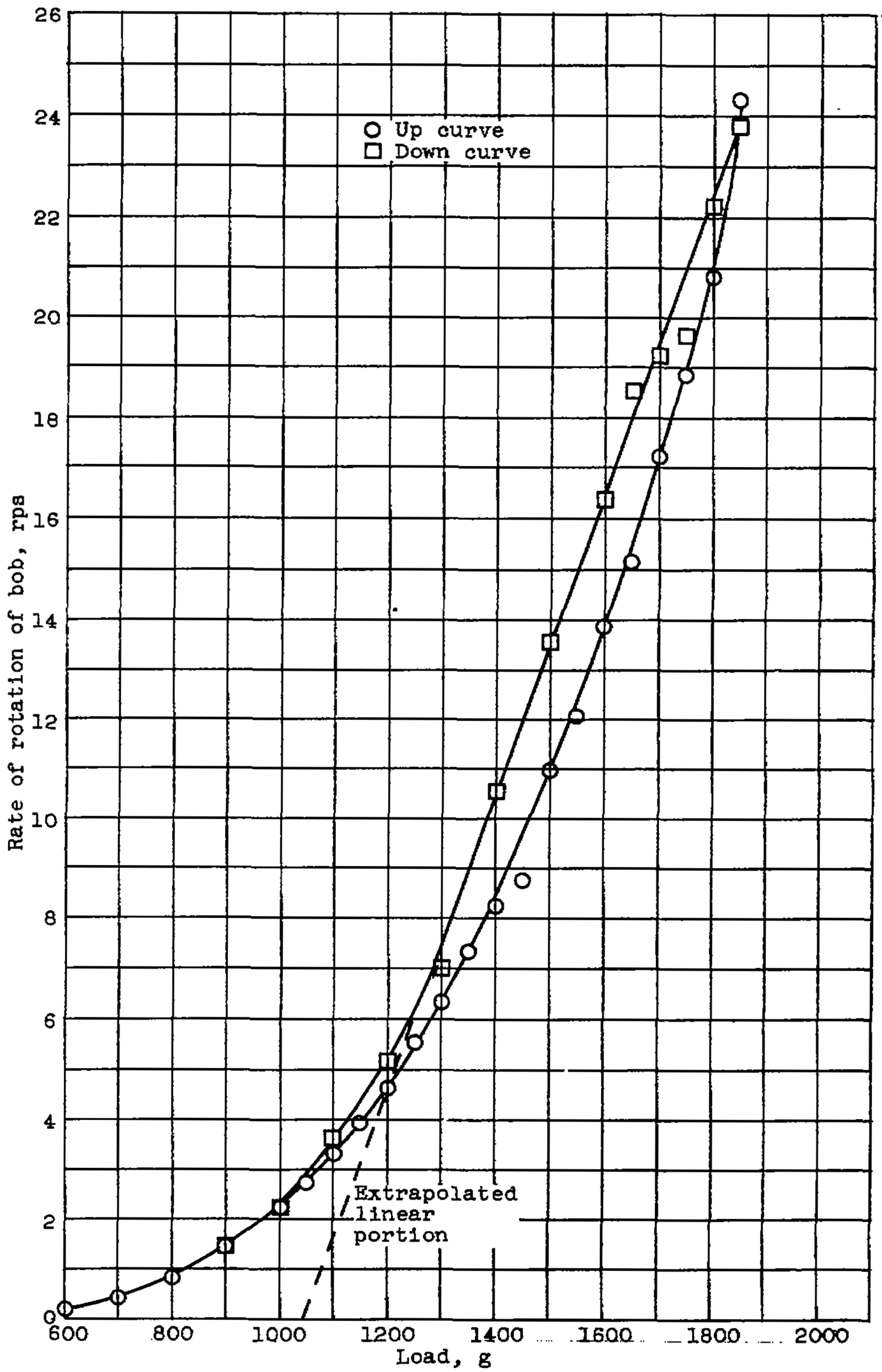
Figure 2. - Photomicrograph of vapor-process magnesium in FP-1.

3834



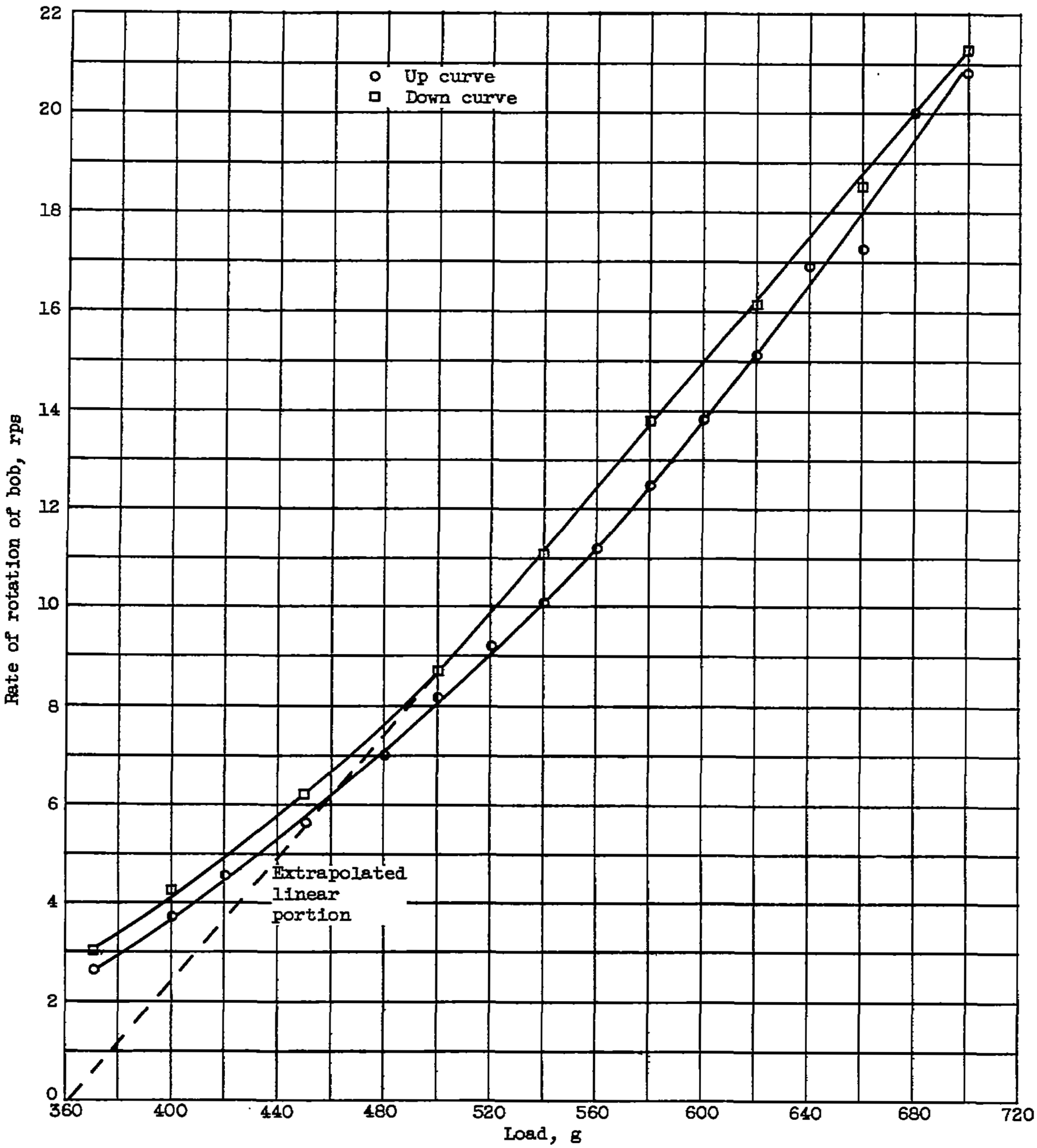
(a) No additive.

Figure 3. - Effect of concentration of additive on flow curve of vapor-process-magnesium slurry.



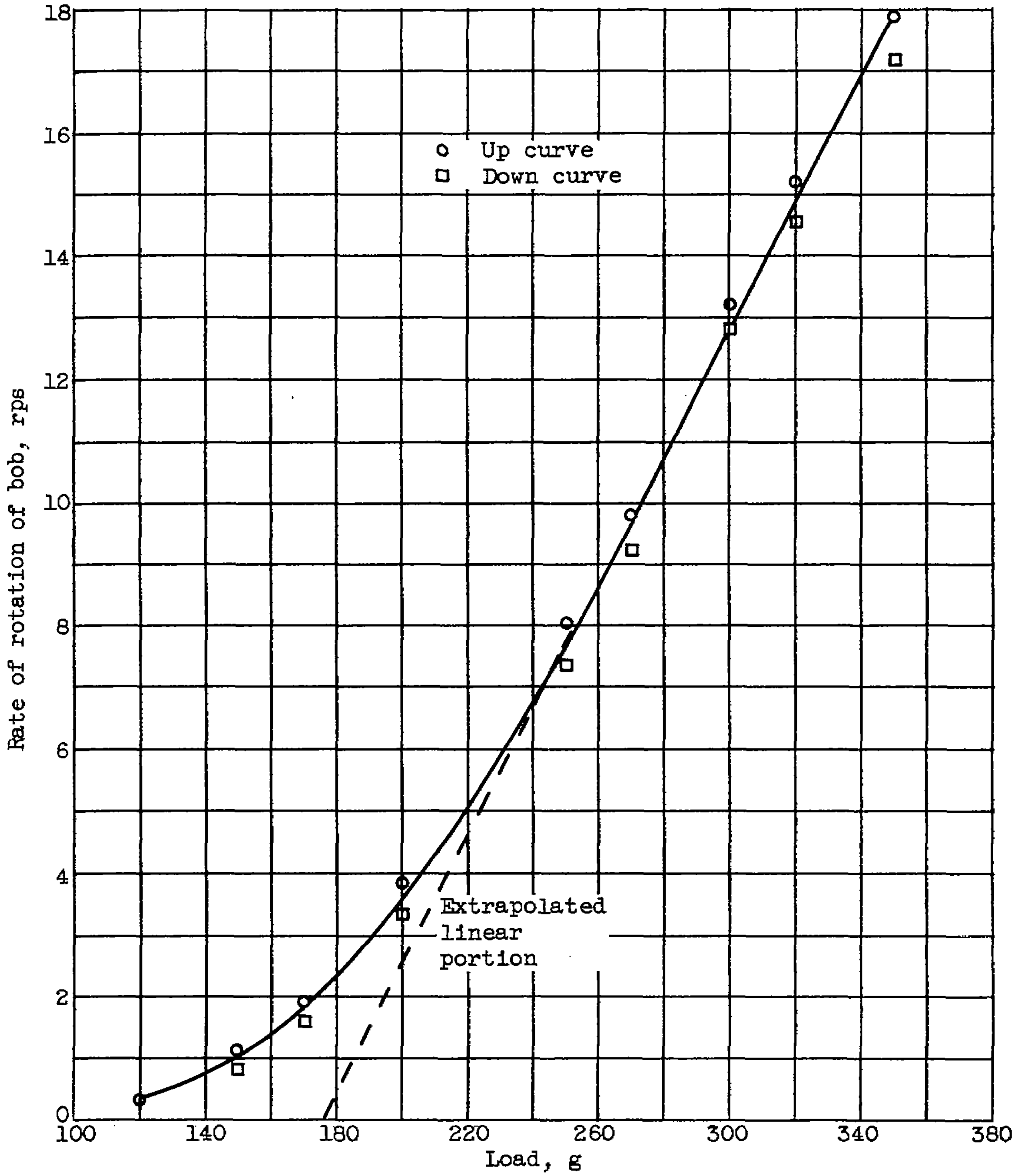
(b) 0.5 Percent polyoxyethylene sorbitol tetraoleate (A132).

Figure 3. - Continued. Effect of concentration of additive on flow curve of vapor-process-magnesium slurry.



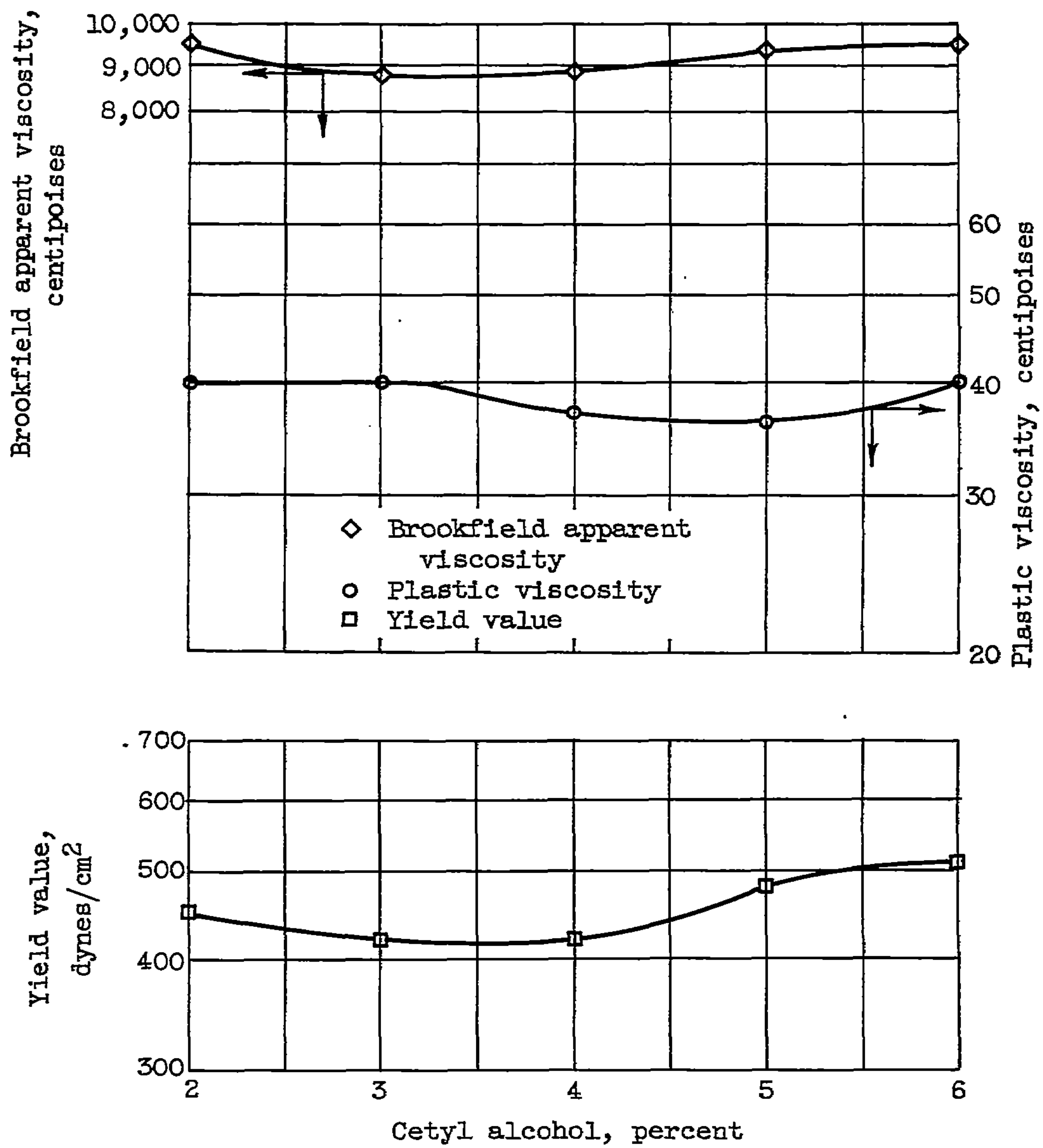
(c) 1.0 Percent polyoxyethylene sorbitol tetraoleate (A132).

Figure 3. - Continued. Effect of concentration of additive on flow curve of vapor-process-magnesium slurry.



(d) 2.0 Percent polyoxyethylene sorbitol tetraoleate (A132).

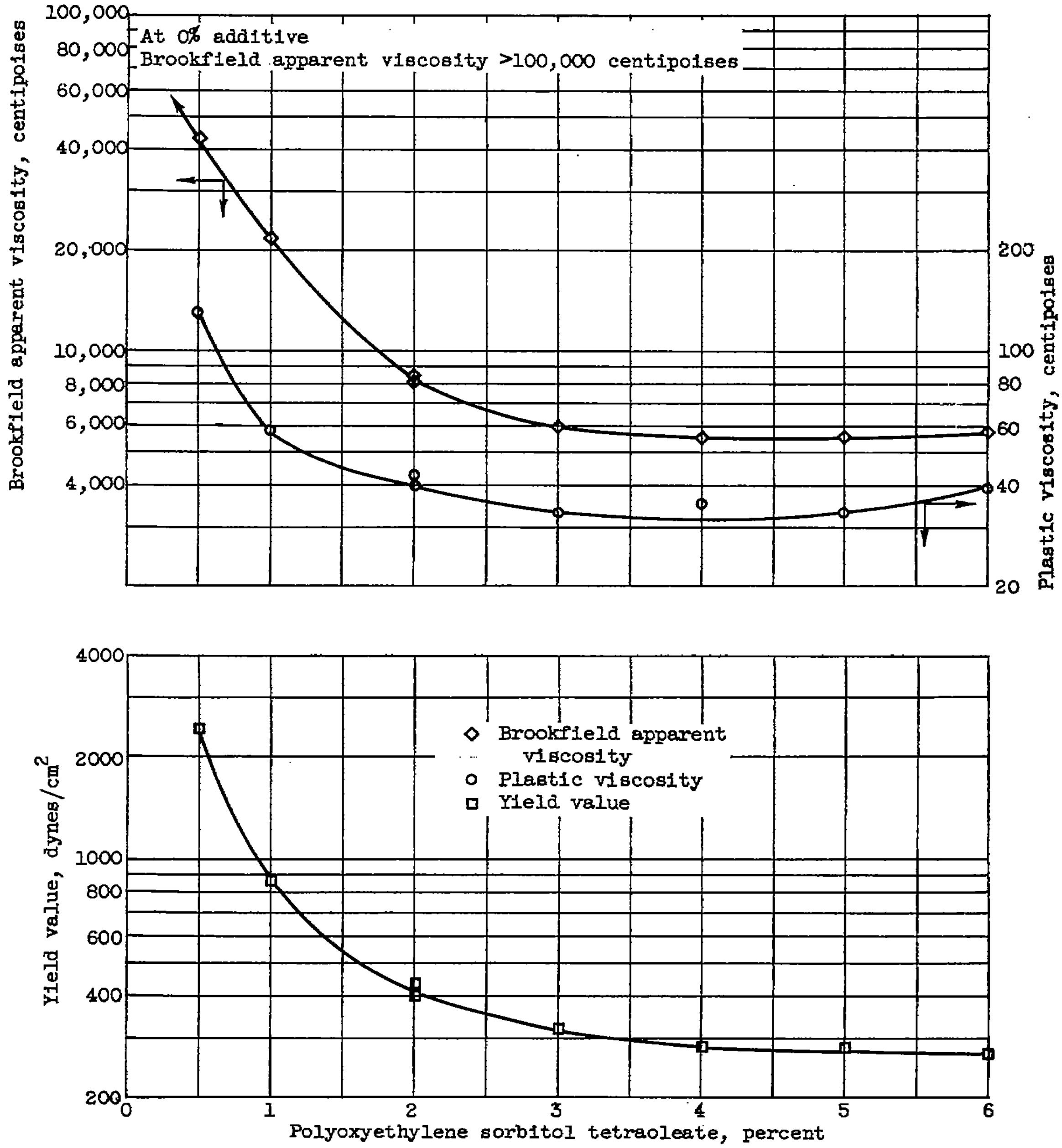
Figure 3. - Concluded. Effect of concentration of additive on flow curve of vapor-process-magnesium slurry.



(a) Additive, cetyl alcohol (A105).

Figure 4. - Effect of concentration of additive on Brookfield apparent viscosity, plastic viscosity, and yield value of vapor-process-magnesium slurry.

3834



(b) Additive, polyoxyethylene sorbitol tetraoleate (A132).

Figure 4. - Concluded. Effect of concentration of additive on Brookfield apparent viscosity, plastic viscosity, and yield value of vapor-process-magnesium slurry.

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